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Selection harvests in Amazonian rainforests: long-term impacts on soil properties

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Abstract

Surface soil properties were compared among disturbance classes associated with a single-tree selection harvest study installed in 1979 in the Brazilian Amazon. Response variables included pH, total N, total organic C, extractable P, exchangeable K, Ca, Mg, and bulk density. In general, concentrations of all elements displayed residual effects 16 years after harvests with N, P, K, and C being inversely related to disturbance intensity while Ca and Mg levels as well as pH were directly related. Elemental contents exhibited fewer residual effects except in the cases of Ca and Mg contents which generally increased with disturbance intensity. Higher intensity disturbance classes were associated with increased bulk density. Soil impacts apparent after 16 years suggest a combination of direct effects of harvests (e.g. as in the case of bulk density) combined with indirect influences of the ecophysiology of the *Cecropia* sp. which dominate disturbed areas. © 1997 Elsevier Science B.V.

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1. Introduction

Sustained integrity and function of forest ecosystems is a major concern world wide. The need to insure the continued satisfaction of human needs derived from forests is especially strong in association with tropical rain forests. These biomes are highly valued for timber resources and non-timber values such as biological diversity, carbon cycling functions, and effects on global climate. Historically, however, these forests have been used in a destructive manner such as slash and burn agriculture, unrestricted logging, and conversion to other land uses. Faced with increasing population pressures and the need for economic growth, countries with tropical forests often turn to these exploitive strategies to make their forests economically productive.

Sustainable development of tropical forests has been defined by FAO (cited by Dykstra and Heinrich, 1992) as "the management and conservation of the natural resource base and the orientation of tech-

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It is unclear whether changes in availability reflect net changes in quantities and if so, whether they are a critical factor in controlling revegetation patterns (Harcombe, 1980). Alternatively, Jordan and Herrera (1981) have argued that disturbance of tropical forests on low fertility sites such as occur in much of the Amazon River Basin will cause large nutrient losses and, subsequently, major decreases in productivity. Similarly, the degree to which harvesting traffic and subsequent changes in soil physical properties may affect patterns of nutrient availability/export after disturbance is uncertain.

Our objective in the current study was to compare current soil properties among four disturbance classes on plots which had been selectively harvested in 1979. We hypothesized that disturbances associated with single-tree selection harvests using planned access would stimulate only short-term shifts in macronutrient availability and that those would be undetectable after 16 years. Similarly, we expected that increases in bulk density and net changes in quantities of soil C, N, P, K, Ca, and Mg would not be detectable after the same time period.

2. Study area

The investigation took place on the Tapajós National Forest which is located in the state of Pará and near the city of Santarém in the Amazon River Basin. The geographic coordinates of the Tapajós are 2°40′S to 4°10′S and 54°45′W to 55°00′W. The Tapajós is bordered on the west by the Tapajós river, to the east by the Santarém–Cuiabá highway between km 50 to 205, to the south by the Santa Cruz and Cupari rivers, while diminishing to a point on the northern boundary. Soils on the Tapajós may be categorized in the orthox suborder in the United States system or Ferralsol in the FAO/UNESCO system (SUDAM, 1989) with a solum depth frequently beyond 2 m. Texture is clayey (i.e. approximately 80%) although these soils are usually well drained, permeable, and highly resistant to erosion. Originating from Tertiary sediments of variable texture, the base saturation is usually low. The A horizon is typically weak while the B may average above 150 cm depth (Hernandez et al., 1993). The geomorphology of the forest can be described as a wide plateau (120–170 m altitude) on the eastern side of the forest that is gradually dissected into increasingly deeper ravines and steep valleys until reaching the flood plain of the Tapajós river on the west. The study site is located on the eastern side of the forest on flat topography undissected by water channels.

The vegetation is primary high forest and dominant over- and understory species are listed in Silva et al. (1995). A short, dry season exists during August–October when rainfall is less than 60 mm month^{-1} and accounts for about 4% of the annual total of 2100 mm. Monthly rainfall is maximized in March, April, and May with averages above 300 mm month^{-1}, corresponding to 48% of annual rainfall (Hernandez et al., 1993). Average monthly temperatures vary from 24.3 to 25.8°C (Silva et al., 1995).

3. Methods

3.1. Treatment establishment

In 1979, a single replication of three treatment plots were designated and subjected to the following treatments: control (24 ha), single-tree selection harvest of all commercial timber > 55 cm DBH (25 ha), and selection harvest of all commercial species > 45 cm DBH (39 ha). Harvests were preceded by an inventory and mapping of all commercial species. Layout of primary skid trails was oriented at regular intervals in an east–west direction and that of secondary trails according to locations of individual trees. No soil data were collected prior to or immediately following the 1979 harvests. According to Silva et al. (1995), the logging intensity was heavy relative to that usually observed in Amazonian selection harvests. An average of 16 trees ha^{-1} from 63 species were removed which translates to a volume extraction of 75 m^3 ha^{-1}.

3.2. Field sampling

All field sampling for the current study took place during January, 1995. On harvest plots, three categories of disturbance were designated for sampling and included (a) minimally disturbed (i.e. any area on a harvest plot not falling within a skid trail), (b) between ruts on skid trails, and (c) within ruts on

4. Results

Ruts in skid trails were still visible after 16 years and the depths and widths of ruts averaged 16 and 97 cm, respectively. In general, skid trails were occupied by *Cecropia* sp., a common pioneer during secondary succession in tropical rainforests (Alvarez-Buylla and Garcia-Barrios, 1991). According to J. Francis (unpublished reports, 1996), the three species of *Cecropia* which occur on the Tapajós include *C. bicolor* Klotzsch, *palmata* Willd., and *sciadolphylla* Mart. There were no significant differences between primary and secondary skid trail data for any response variable and, consequently, those data were pooled by disturbance class.

Comparisons of concentration data for N, P, K, Ca, Mg among classes indicated that levels of all elements remained affected to varying degrees by harvesting after 16 years (Tables 1 and 2). In general, concentrations of N, P, K, and C decreased with disturbance intensity while those of Ca and Mg increased. Bulk density and pH both increased directly with intensity. In addition, there were significant changes in bulk density, Ca, and Mg between the controls vs minimally disturbed areas, a potentially, very important finding in relation to the high proportion of area associated with the latter disturbance class.

Nitrogen, P, and pH effects were most strongly pronounced when skid trail versus non-skid trail samples were compared. There was no difference for N, P, or pH when controls were compared with minimally disturbed areas. Calcium and Mg exhibited tandem behavior and, as mentioned, were altered even in minimally disturbed areas. Carbon concentrations were different only when the most divergent classes were compared. Bulk density data indicated that soils remained compacted in all classes after 16 years. Potassium was the least responsive of any element to disturbance after this time period. Although C/N ratios generally widened as disturbance increased, (i.e. 13.3 to 13.9) differences among classes were not significant.

Comparisons of net changes in elemental content to a depth of 7.6 cm indicated fewer statistically significant shifts than did the concentration data (Tables 3 and 4). There were no significant shifts for N, K, or C. However, significant increases in content of both Ca and Mg were evident as disturbance increased except in the within vs between-rut comparisons.

In 1995, the visible extent of areal disturbance associated with each disturbance class was similar on the 45- and 55-cm plots and averaged as follows: primary skid trails, 1%; secondary skid trails, 0.1%; and minimally disturbed areas, 99%. However, the extent of areal disturbance at the time of harvest in

Table 2
Probability levels associated with paired-comparisons of Table 1 data among disturbance classes on harvested sites in the Brazilian Amazon

Comparison	BD	pH	N	P	K	Ca	Mg	C
Control–rut	0.00	0.03	0.00	0.04	0.08	0.00	0.00	0.06
Control–min. dist.	0.10	0.94	0.31	0.84	0.34	0.00	0.00	0.61
Control–middle	0.00	0.00	0.02	0.07	0.13	0.00	0.00	0.18
Min. dist.–rut	0.00	0.00	0.01	0.01	0.32	0.22	0.10	0.09
Min. dist.–middle	0.01	0.00	0.10	0.02	0.36	0.19	0.13	0.25
Middle–rut	0.01	0.32	0.40	0.81	0.99	0.82	0.84	0.61

Table 3
Content (g m^{-2} to 5 cm depth) of N, P, K, Ca, Mg, and C by disturbance classes on harvested sites in the Brazilian Amazon. Standard errors in parentheses

Class	N	P	K	Ca	Mg	C
Control	178.6	0.33	2.96	0.29	0.18	2393
	(3.97)	(0.02)	(0.18)	(0.03)	(0.03)	(107)
Minimally disturbed	178.8	0.35	2.91	0.54	0.30	2432
	(3.98)	(0.01)	(0.11)	(0.06)	(0.02)	(67)
Skid trails middle	178.8	0.31	2.91	0.73	0.40	2446
	(3.58)	(0.02)	(0.11)	(0.10)	(0.04)	(72)
Skid trails ruts	183.4	0.32	3.07	0.75	0.41	2524
	(1.73)	(0.02)	(0.11)	(0.10)	(0.03)	(74)

Table 4
Probability levels associated with paired-comparisons of Table 3 data among disturbance classes on harvested sites in the Brazilian Amazon

Comparison	N	P	K	Ca	Mg	C
Control–rut	0.56	0.75	0.60	0.00	0.00	0.32
Control–min. dist.	0.98	0.49	0.79	0.00	0.00	0.76
Control–middle	0.98	0.44	0.81	0.00	0.00	0.68
Min. dist.–rut	0.46	0.20	0.30	0.06	0.01	0.35
Min. dist.–middle	1.00	0.06	0.98	0.10	0.04	0.89
Middle–rut	0.44	0.60	0.32	0.90	0.82	0.45

tropical forest demands compared with those of N and P (Sanchez, 1992).

Based on the evidence that organic N and C concentrations are reduced in the heavy disturbance classes, we believe that the conversion of above- and/or belowground detritus to soil organic matter (SOM) has been altered in the heavy disturbance classes. This could result from restricted root growth in the upper 7.6 cm of mineral soil due to residual compaction, different root architecture associated with *Cecropia* sp. (i.e. greater tendency for roots to occur in the 0 horizon), or differential quality (i.e. slower decomposition) of *Cecropia* sp. detritus. It is possible that P and K trends are associated with the same SOM linkage.

6. Conclusion

It should not be surprising that long-term effects of harvesting in systems with very strong biogeochemical linkages between vegetation and soil are heavily influenced by the ecophysiology of pioneer vegetation species. However, an interaction between residual soil compaction and vegetation cannot be eliminated as a possible explanation for some of the results presented here. It is apparent that, although soil C was assessed only to a very shallow depth, no evidence of net soil C source or sink behavior existed after 16 years.

Given the tendency for *Cecropia* sp. to colonize natural gaps, it is likely that single-tree selection harvests in the Tapajós mimic processes ongoing in gap-phase regeneration to some degree. This may reflect a major difference between selection harvests vs tropical clearcuts since early successional patterns may be disrupted in the clearcuts (Alvarez-Buylla and Garcia-Barrios, 1991). The combination of small canopy openings and soil disturbance associated with selection harvests may resemble conditions created by an upturned tree, a scenario that is conducive to the establishment of pioneer vegetation such as *Cecropia* sp. (Putz, 1983).

However, a better understanding is needed of the degree to which the soil conditions described here are similar to those associated with gap-phase regeneration. If soil processes differ between the two modes of gap creation, the distinction could be important to the sustained management of these ecosystems since even the minimally disturbed areas (i.e. 99% of the harvested area) continue to show evidence of compaction and biogeochemical differences.

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